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Research paper

From Paris agreement to business cases for upgraded biogas: Analysis of potential market uptake for biomethane plants in Germany using biogenic carbon capture and utilization technologies

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ABSTRACT

The Paris Agreement brings countries together in a combined effort to combat climate change and its effects. A key target is the reduction of energy related greenhouse gas emissions. Providing biogas from biomass is one option to provide renewable and less carbon intensive fuels. When upgraded to biomethane it may be a substitute for natural gas and thus may have many application pathways. Recognising this potential many European countries installed governmental support programmes to stimulate market growth over the last decade. However, most of the installed schemes in Europe are time-limited. Besides being time-limited most of the schemes include a degression of compensation over time, resulting in many having limited success over longer time frames. This study questions the feasibility of near-term business cases for biomethane plants and analyses options for making them less dependent on governmental support programmes. Currently a market potential is seen in the utilization of process carbon dioxide in carbon capture and utilization or carbon capture and storage pathways, because it is a widely available side product from biogas upgrading. Therefore, we examined three business cases for its utilization in across sectors. To answer the research question we use a previously developed biomethane market simulation model and added an extension for new business cases. Results indicate that there are specific business options in the field of 2160 $m^3\ h^{-1}$ to 20,840 $m^3\ h^{-1}$ that are economical feasible under certain circumstances.

1. Introduction

The Paris Agreement brings countries together in a common effort to combat climate change and its effects. A key target is the reduction of energy-related greenhouse gas (GHG) emissions. Substituting fossil energy carriers through low carbon renewable options is a key pathway to reduce emissions. Amongst the renewable energy carriers, biomethane produced from the upgrading of biogas is an interesting option as it can be a 'drop-in' fuel that can directly substitute fossil energy carriers using the existing energy infrastructure. Biogas is upgraded to biomethane through the separation of mainly sulphur, hydrogen and carbon dioxide. After the process of upgrading biomethane, it is chemically equal to natural gas.

Many European countries have recognised the potential of biomethane to decarbonise their natural gas infrastructure and have designed governmental support programmes to stimulate market development [1]. However, governmental supports will most likely decrease in phases as there is a transition to an independent market. Indeed, most of the installed schemes in Europe are time-limited. The leading biomethane producing country in Europe is Germany with currently about 196 biomethane plants producing about 122,000 $m^3\ h^{-1}$ biomethane which is used to directly substitute natural gas [2]. As Germany is the leading market for biomethane in Europe and has started to reduce governmental compensation by simultaneously advertising the transformation to a more market-oriented approach, it serves as a case study for a European issue: what are feasible near-term business cases for biomethane plants making them less dependent on governmental support programmes.

The build-up of a biomethane market in Germany was heavily related to governmental support programmes like the Renewable Energy Act (REA) [3], the Renewable Heating Act (RHA) [4] and the Biofuel Quota (BQ) [5]. The most important support instrument for the market

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development was the REA. It guarantees a financial support for the electricity produced from biomethane use in combined heat and power (CHP) plants over a period of 20 years. The utilization of biomethane in the transport sector and the heating sector is framed by regulations and laws, encompassing i.e. quotas, tax reliefs and sustainability requirements, but is not supported through direct financial incitement. In contrast, the utilization of biomethane in the transport and heating sector is dependent on customers willing to buy a more environmental friendly product [6].

A challenge arising within the next decade in Europe and especially for the German biomethane market is the situation when the financial support from REA ends after a period of 20 years, which will affect biomethane plants from 2026 onward. The level of financial support has changed as a result of several amendments to the REA and is currently too low to support on-going biomethane production for the existing plants beyond 2026 [7]. In parallel, incentives for the heat and transport market are not yet well developed [8,9]. The question arose, what are the effects of these support scheme changes on the biomethane market in Germany - the production capacity, substitution pathways and thus GHG emission savings. In a previous study we have shown the effects of the current legal framework as well as changes of the legal framework to the biomethane market until 2035 [10]. Results indicate that revenues from current governmental support programmes as well as revised ones are insufficient for an ongoing operation of biomethane plants. However, the majority of biomethane plants need new business opportunities in the next decade to reduce redundancies from REA and secure an on-going operation and biomethane production. One business opportunity is potentially increased intra-European trade of biomethane, but this is not the focus of this study [11]. Another promising business opportunity is currently seen in the provision of renewable carbon for carbon capture and utilization (CCU) demanded by national climate protection strategies and according to Paris Agreement. During the processing of biogas to biomethane so called “off-gas”, consisting mainly of CO_2, is produced. This biogenic CO_2 is not burdened with climate-relevant emissions and is well suited as base product for diverse utilization pathways [12]. In addition, biomethane plants can generate additional income, which might help them to compensate the impending loss of financial support from the government. As Germany by a large margin is the leading proponent of biogas in Europe [13] how the German market diversifies and adapts to the reducing financial supports will likely provide many lessons for other countries.

In the past decades climate change came to the fore and technologies have been developed that incorporate the use of the climate-affecting exhaust gas CO_2 as a raw material for industrial production processes and liquid or gaseous energy carriers and thus to imitate a natural carbon cycle [14]. The use of biogenic CO_2 is aimed at substituting fossil carbon sources and is often associated with the transformation of the energy supply from fossil to renewable energy sources [15]. Within this study, we focus on CO_2 as a potential commodity from biogas/biomethane, generated during the upgrading process. Furthermore, we included background information on the size of the CCU potential from biogas and biomethane production in Germany. In addition, detailed background information on sustainability issues associated with the use of bioenergy with carbon capture and storage (BECCS) is presented.

The industrial use of CO_2 for the production of liquid and gaseous energy carriers as well as chemical products is an important and current topic in politics, industry and research. Many new technologies are being developed, tested and are close to market implementation [16]. A further dynamic in market development is expected in this sector, as the use of CO_2 with renewable energies holds great potential, especially the combination of biomass applications and CCU-applications [17].

It is the aim of this study to evaluate the economic possibilities of CO_2 utilization generated by biomethane plants in Germany, and therefore takes steps forward in answering the question whether the presented approaches are capable of generating sufficient additional value for currently operating biomethane plants beyond 2026. This is done via an extension of the dynamic market simulation model for the German biomethane market BiMaSiMo (Biomethane Market Simulation Model). We identified three promising business options associated with CCU and biomethane plants, these being exemplarily for other applications and suitable for a ranges of plant sizes:

- Business Case 1: combined production of bio-LNG (biomass based liquefied natural gas) and dry ice via a cryogenic approach.
- Business Case 2: utilization of CO_2 in the chemical industry
- Business Case 3: production of high value chemicals.

The production of bio-LNG and dry ice is potentially a favourable option for plants with a gas flow $< 250\,m^3\,h^{-1}$, 0whereas the production of high value chemicals is seen favourable options for plants of about $125\,m^3\,h^{-1}$. Business case 2 needs larger amounts of gas flow of about $1200\,m^3\,h^{-1}$. It has to be mentioned that the identified business options are between demonstration phase and close to market implementation and estimated prices, capital expenditure (CAPEX), operational expenditure (OPEX), etc. are derived from literature, research projects, and process simulations. Nevertheless, in combination with BiMaSiMo it is possible to estimate the future business prospects of the presented case studies using contrasting market uptake scenarios and assumptions.

The originality of our approach is justified by the fact that research provides innovative technologies that will most likely help to secure a more environmentally friendly energy supply but sometimes fail in providing estimates or needed conditions for a future market uptake of those technologies [18,19]. The research modelling tool is able to estimate the future market uptake demonstrated in this case study for three promising technologies for carbon capture and utilization in association with biomethane production. The demand of viable, sustainable and economic feasible CO_2-removal techniques to deliver the goal of the Paris agreement a primary target of limiting global temperature rise to 2 K, equivalent to restricting atmsospheric CO_2eq concentrations of 430–480 ppm by 2100. 101 of the 116 Intergovernmental Panel on Climate Change's 430–480 ppm CO_{2eq} scenarios rely on negative emission technologies, where BECCS is the primary technology targeted. Bioenergy with CCU may provide pathways for increasing the cost effectiveness of bioenergy negative emission technologies to meet the Paris Agreement target.

2. Methodology

In this study, we update and apply a market simulation model developed for the German biomethane market to account for the latest research where CO_2 is produced during biomethane production. The business cases analysed were developed to account for various plant sizes and to represent case studies of technologies that are close to market implementation. References from literature, research project publications and specific consultations with researchers involved in the economics of projects were collated (Appendix A, Table 1, Table 2, Table 3) and transformed into a system dynamics sub-model. This was then connected to BiMaSiMo which was built using system dynamics methodology and VENSIM software [20,21].

2.1. Retrospect BiMaSiMo

BiMaSiMo is a dynamic market simulation model, which currently encompasses the German biomethane market. The model is able to simulate the effects of changes in the legal framework, regulatory framework, market conditions or the diffusion of innovative technologies in terms of biomethane production capacity, natural gas substitution pathways, GHG emission savings and biomethane potential development. For this research it is calibrated for a simulation period of 2000–2035. The use of BiMaSiMo is justified by the model's innovative

capability of analysing each of the relevant markets – power, heating and transport. In addition, it is able to estimate the future production capacity rather than using predefined trajectories as with many other studies. BiMaSiMo has proven its suitability to provide validated simulations of the investments in the German biomethane market made under varying scenarios, regarding profitability, supply and demand interactions, and policy interactions linking the three sectors power, heat and transport market. The interactions between the biomethane supply sectors justify the use of system dynamics modelling techniques as it allows analysis of systems (market) behaviours (investment) to changes in the system (legal framework, resource potential, etc.). BiMaSiMo is fully described externally [10]. The key assumptions of the model are:

- Model is driven by the energy demand of Germany that can be fulfilled by gaseous fuels up to 2035,
- Consists of cases studies of eleven model plants between 180 and 4029 kW of electrical power with varying provision modes and cost-benefit calculation determining economic side of supply for biomethane and natural gas
- Revenues can be generated from power production, heat production, transport fuel production and governmental support
- Biomethane and natural gas is limited by feedstock and/or land availability
- Model accounts for 'green customers' who are willing to pay a premium for green energy in the direct heating market and the transport market according to a decision influenced by economic and environmental aspects
- Policy adjustments are influenced by green customers, capacity development and the performance and development of the cost-benefit calculation

2.2. Additional model parts of BiMaSiMo for the presented business cases

To simulate a conceivable market diffusion of innovative business cases for biomethane plants a modified Bass Diffusion Model (BDM) partially introduced by Sterman was used [21]. We incorporated growth in the size of the total market. Subsequently the modified BDM was linked to the part of the model calculating production for a representative biomethane plant as well as CAPEX, OPEX and the total attractiveness of the product compared to fossil alternative. This process is shown in the causal-loop-diagram (CLD) displayed in Fig. 1.

The presented causal-loop-diagram (Fig. 1) was designed equally for the three business cases. It illustrates feedback structures and causal relationships of the system and within the newly developed sub-model. In addition the linkage to BiMaSiMo is shown by the dotted arrow. The Loops 1–3 identify the three feedback structures of the sub-model.

Loop 1 shows the relationship between *potential adopters* and the *adoption rate from word-of-mouth* (+) which in turn influences the *number of adopters* (+). An increasing *number of adopters* will decrease the *potential adopters* (−). Loop 2 shows the relationship between *potential adopters* and the *adoption rate from advertising* (+). The *adoption rate from advertising* influences in turn the *number of adopters* (+). The loop is closed with the linkage to the *potential adopters* (−). Loop 3 shows the linkage of *annual podution* and CAPEX (−).

2.3. Model validation

Model validation is a highly important step in system dynamics modelling involving quantitative and qualitative parts. However, it is important to remember that a system dynamics model is not intended to deliver specific predictions but a deeper understanding of dynamic systems behaviours such as markets and value chains. It can be said that there is no fully valid system dynamics model because a model is always a reduction of the real system, thus it is more valuable to talk about usefulness. A useful model needs to be able to replicate the behaviour of the systems it is referring to. Otherwise, the model provides only little useful information about the structure and the behaviour of the real system. Here, a statistical comparison was made between the historical data and the baseline of BiMaSiMo. A sensitivity analysis is presented in Ref. [10]. Results of model validation are presented in section 4.

2.4. Detail information on business cases for biomethane and CCU

2.4.1. Business case 1 - Bio-LNG plus dry ice

Our first business case for biomethane plants in Germany is the combination of dry ice production and bio-LNG production using a combined cryogenic approach for biogas upgrading and liquefaction. Cryogenic biogas upgrading has been much discussed recently mainly due to the possibility to also produce bio-LNG, which has benefits regarding energy density and transportability [22]. Cryogenic separation processes are generally rather complex and in most cases more costly than other upgrading approaches. For this business case it would be necessary to either replace the currently used upgrading unit by a cryogenic upgrading unit or to install an additional cryogenic

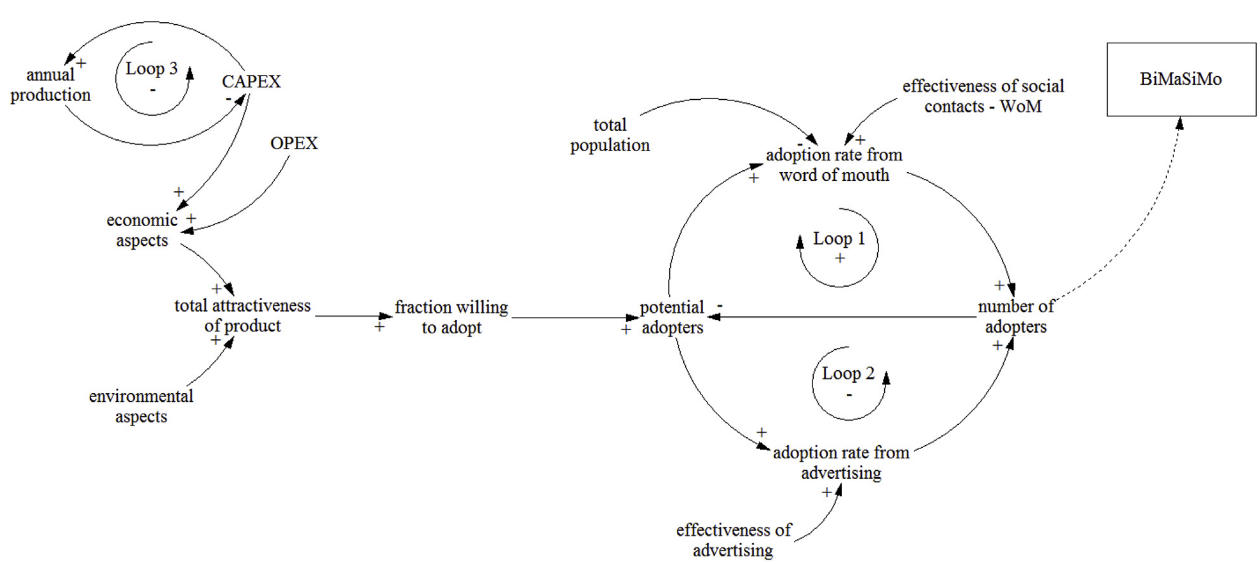

Fig. 1. Causal-Loop-Diagram of additional parts of BiMaSiMo.

upgrading unit and use just a proportion of the gas flow. One approach being able to produce dry ice and bio-LNG simultaneously is the cryogenic temperature sublimation approach. This process is of high interest for gas flows < 250 m^3 h^{-1} mainly because alternative upgrading processes are not economical. The separated CO_2 can be used as dry ice (material use or energetic use). The produced bio-LNG can be used as a substitute of fossil LNG. At first biogas is pre-cooled to 193.15 K and subsequently exempted from CO_2 through further cooling to 123.15 K. In this process step, the CO_2 falls out in form of dry ice and is intended to be partially used for the precooling of the biogas. Finally, the gaseous methane is liquefied at 111.15 K. The gradual cooling takes place by passing biogas over several heat exchangers.

In order to sell the CO_2 generated by the cryogenic temperature sublimation approach process, there are two distribution channels: either a direct sale to the end-user of CO_2, or the sale to one of the large gas companies or traders dealing with dry ice. It is important to consider the amount of CO_2 produced and the distance to the end customer as well as their purchase volume. The largest amounts of dry ice are consumed by the food industry, in dry ice service companies as well as in the chemical and pharmaceutical industry. In these areas a high fabric quality is demanded. Currently the dry ice market in Germany has a size of around 150,000 Mg a^{-1} and is adequately served [22]. However, a better availability of large amounts of dry ice could lead to a price degression but at the same time establish new sales markets.

The global LNG market has grown by an average of 7% over the last few years. It is developing more dynamically than the market for pipeline gas. The global trade volume was about 241 million Mg in 2014 (equivalent to 313 billion m^3 natural gas). To date, LNG has mainly been an import product. However, new business options and possible applications are opening up whilst the importance of LNG as fuel increases, especially in heavy-load traffic on the road, sea and inland waterways [23,24]. In addition, LNG is predestined for gas supply without access to the gas network due to its economic feasible road transport potential. Therefore there are several attractive possibilities for opening up new end-user markets for LNG [25]. In order to decarbonise this sector biogenic sources of LNG have to be considered. The most interesting scope of application for biogenic LNG is as fuel in the area of heavy duty vehicles and shipping, due to the high energy density of LNG. First of all because the use of liquid methane is considered as an alternative to reduce pollutants, particulate matter and CO_2 emissions. Even blending of fossil LNG with its biogenic alternative from waste will improve the climate footprint. The most important simulation parameters are shown in table 1 in Appendix A.

2.4.2. Business case 2 - CO_2 streams for the chemical industry

The second business case describes the utilization of CO_2 from biogas upgrading, which is currently largely unused for chemicals. There is a wide range of possible chemical products, see section 3.1. In most cases H_2 is used as the reaction partner, and a promising option is the processing to methanol (CH_3OH) [26]. Methanol is one of the most important basic materials in the chemical industry. On the one hand, methanol can be used directly as a fuel and thus biogenic methanol would be a suitable alternative for gasoline or diesel and reduce GHG emissions significantly. Methanol is also a platform chemical which can be used to process a wide range of chemicals, e.g. formaldehyde and acetic acid. One main requirement for an economic and ecological friendly conversion of biomass respective biogenic CO_2 into methanol is the provision of low price and sustainable H_2. The production of H_2 via electrolysis from excess power (e.g. from photovoltaic or wind) is a very promising pathway. The emission factor of the H_2 respective the electric energy will have a crucial impact on the overall life cycle assessment. Equation (1) shows the conversion of methanol by CO_2 and H_2.

$$\boldsymbol{CO_2} + 3\,\boldsymbol{H_2} \rightarrow \boldsymbol{CH_3OH} + \boldsymbol{H_2O} \tag{1}$$

The investment and operation cost of typical biogas and biogas upgrading processes are generated by calculations based on a previous study [27]. The extent of the biogas processes are directly linked to the methanol processes as to balance the demands of CO_2. For simplification reasons we did not conduct a comprehensive feasibility study for the H_2 production. Instead the cost calculation for H_2 by exhaust power from renewable energies is being used [28]. Additionally the H_2 costs are varied in order to evaluate the effect of the H_2 overall process. The most important simulation parameters are shown in Table 2 in Appendix A.

2.4.3. Business case 3 - production of high value waxes

The assumptions of this business case were derived from preliminary results of an ongoing research project [29]. However, the values used in this research are done so to provide a first estimate on the business possibilities of this novel utilization pathway in biogas value chains. The production of high value chemicals and waxes in particular via Fischer-Tropsch synthesis is the third business option presented in this study. The absence of aromatic and polycyclic aromatic compounds means the production of waxes out of Fischer-Tropsch synthesis especially suitable for the production of cosmetic products. Whereas Fischer-Tropsch synthesis has proceeded in large scale plants (> 1600 m^3 day^{-1}) using natural gas and coal as feedstock since the 1940`s, small-scale applications (160–1600 m^3 day^{-1}) were discussed in literature recently [30,31]. Due to its composition biogas and thus biomethane are particularly suitable for the production of high value chemicals and waxes. The process steps for the production of high value chemicals encompass syngas production, Fischer-Tropsch synthesis and product separation. The reforming can be done via autothermal reforming or steam reforming of biogas. Our proposed business case focuses on small scale application steam reforming as this is a simple and thus cost-efficient process. The shift towards synthetic and sustainably produced waxes is going to keep its momentum [32]. Biowaxes are particularly well suited for people having allergies or intolerances on petroleum based waxes. In contrast to fossil wax alternatives like beeswax, biowaxes from biogas provide a more sustainable alternative for the organic cosmetic industry. The most important simulation parameters are shown in table 3 in Appendix A.

3. Background information on CO_2 potential, markets and sustainability aspects

3.1. CO_2 emissions and associated global CCU potential

Currently there is an annual global demand of CO_2 as substrate of ~200,10^9 kg (2013) [33]. The majority of this is synthesized to urea (58%), inorganic carbonates (25%) and methanol (4%); whilst the share of the direct utilization (beverage carbonization, food packing and industrial gas) is about 9%. Aresta et al. (2013) and Naims (2016) calculated a near term demand of ~250,10^9 kg, with the highest increase within the material branch [33,34]. Currently global anthropogenic CO_2 emissions may be summed up to total around 32,000 10^9 kg, the majority is fossil fuel sources [35]. Compared to the total global emissions, the potential CO_2 utilization is quite limited, because not all of the emissions are suitable (under regard of reasonable efforts) to be captured and utilized. The near term CO_2 demand has been calculated at 250,10^9 kg, with the estimated long term CCU potential estimated to be 1500–2000 10^9 kg a^{-1} [36]. Thus, up to 6% of anthropogenic CO_2 can be captured within a constant loop of demand, under regard of the chosen assumptions. A drastically change in e.g. consumer behaviour (acceptance) or policy regulations can lead to a higher CCU potential.

3.2. CCU potential by bioenergy

Bioenergy processes show high potential for a future CO_2 capture and utilization. CO_2 from biogas upgrading has been identified as ideal source for further utilization due to capture cost, specific energy

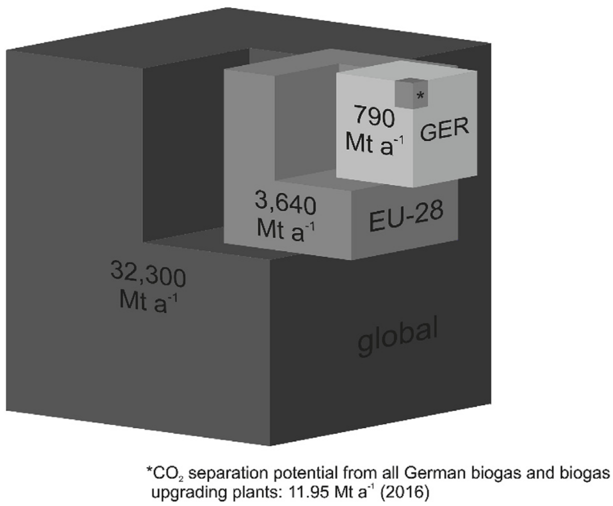

Fig. 2. Global, EU and German CO_2 emissions and biogas and biomethane based CO_2 potential in Germany [35,44].

requirement and CO_2 penalty [37]. A further interesting process is the thermochemical conversion of lignin rich biomass into biogenic synthetic natural gas (bio-SNG).

Biogas consists mainly of methane and CO_2, while commonly methane is the major part with up to 70% [38]. Usually the biogas is directly used within CHP processes (combined heat and power), but it can also be upgraded to biomethane [39]. The typical bio-SNG process is based on substrate pre-treatment (mainly crushing and trying), gasification, syngas treatment, methanation and upgrading of raw gas [40]. Within the upgrading of biogas respective raw gas the CO_2 is separated as by-product, at present state the currently available CO_2 is not typically used and in the most cases injected into the atmosphere. Depending on the upgrading technology the CO_2 is diluted with air or is high concentrated [39]. While the biogas respective biomethane process is already established in the market, the bio-SNG process is still in the research stage and not yet commercially available. Due to high uncertainties of the bio-SNG process and development it is not considered within this study.

In Fig. 2 the global, EU and German CO_2 emissions as well as the theoretical biogas/biomethane based CO_2 potential in Germany is plotted. It assumes a total availability of the whole CO_2 fraction within the biogas and biomethane pathway. This includes all biogas plants (9,016) and all biogas upgrading plants (196) in Germany (end 2016 plant numbers were taken) [41]. This amount is a theoretical number, which requires the CO_2 capture from the exhaust streams of all biogas and biomethane based CHP plants (combined heat power plants) or a converting of all biogas plants to biogas upgrading plants with included CO_2 capture. Based on this assumption there is a yearly potential of 10.4 10^9 kg CO_2 from biogas plants and 1.5 10^9 kg CO_2 from biogas upgrading plants. The calculation is based on the figures of [2,41,42]. Compared to the global, EU and German annual CO_2 emissions, the potential of sustainable CO_2 for carbon capture and utilization (CCU) by biochemical conversion is rather small but important [43].

3.3. Sustainability/environmental effects

The environmental impacts of carbon capture and storage (CCS) and carbon capture and utilization (CCU) technology pathways may vary greatly depending on design and characteristics of the processes. Table 1 presents a summary of potential environmental impacts identified within existing literature where life cycle assessment has been carried to evaluate the environmental performance of CCS and CCU processes. Many of the identified environmental impacts for systems with CCS were associated with the increased demand for fuel to

Table 1
Summary of potential environmental impacts of CCS & CCU technology processes as identified within life cycle assessment research.

Potential Environmental Impacts	Carbon Capture & Storage (CCS)	Carbon Capture & Utilization (CCU)
Abiotic Depletion	✓	✓
Acidification	✓	✓
Eutrophication	✓	✓
Fresh Water Aquatic Ecotoxicity	✓	✗
Marine Aquatic Ecotoxicity	✓	✓
Terrestrial Ecotoxicity	✓	✗
Global Warming	✓	✓
Human Toxicity	✓	✓
Ozone Depletion	✓	✓
Photochemical Ozone Creation	✓	✓
Land Competition	✗	✓
Ionising Radiation	✗	✓
Energy Demand	✗	✓
Water Demand	✗	✓
SOx Emissions	✗	✓
NOx Emissions	✗	✓
Reference Studies:	[45–54]	[55–63]
Key:	✓	- potential for negative environmental impact.
	✗	- no environmental impact identified.

compensate for energy efficiency losses resulting from the use of CCS technologies. In addition, the generation of ammonia emissions released during the absorbance of CO_2 through the active solvents generates further environmental impacts. For CCU technologies high variability in potential environmental impacts was found to be dependent on the choice of CCU technologies and CO_2 utilization pathways.

A primary driver for developing CCS and CCU technologies is to reduce the CO_2 intensity of our energy systems. There is growing dependence particularly on the development and deployment of BECCS technologies to ensure that global emission scenarios do not exceed 2 K warming to prevent dangerous climate change [64]. When comparing both CCS and CCU technology pathways it is essential to analyse the whole system GHG and environmental performances.

Life cycle assessment research by Welfle et al. (2017) found that anaerobic digestion and biomethane combustion pathways can deliver bioenergy with GHG intensities far below the equivalent values of conventional fossil fuel pathways [65]. Although the specific GHG performance of any given bioenergy pathway will be largely determined by the characteristics of the activities and processes over the whole life cycle of the biomass resource and bioenergy processes. For example, energy intensive processes such as upgrading biogas to produce 'grid-grade' biomethane will produce a fuel with increased use and value, but at the detriment of increasing the GHG intensity of any energy generated [65].

Research by Cuéllar-Franca & Azapagic, (2015) provides a direct comparison of the environmental impacts of CCS and CCU technologies, from a whole life cycle GHG performance perspective. Their analysis estimated the global warming potential of CCS options to be 276 kg CO_2eq Mg^{-1} removed CO_2, compared to 59.4 Mg CO_2 eq. Mg^{-1} removed CO_2 for CCU options where the CO_2 was used to generate platform chemicals such as dimethyl-carbonate - the global warming potential for CCU options being up to 216 times greater than for CCS options [66]. Suggesting from a climate change perspective both CCS and CCU technologies are currently far from the ideal solution for mitigating emissions, and may sometimes lead to the delaying or transferring of emissions to other stages of process life cycles rather than permanently eliminating them.

A further potential GHG risk attributed to certain biomethane scenarios where land is used to produce energy crops rather than food

crops, are emissions generated as a result of indirect land use change. The growth of energy crops on lands currently used for food crop production may result in the intensification of food crop production elsewhere and/or further lands being transformed for agriculture uses to meet food demands – land use change being a source of potentially large GHG emissions. As there is no standard method of identifying and measuring indirect land use change processes these potential impacts may be overlooked [67]. From a life cycle assessment perspective any GHG resulting from indirect land use change processes due to energy crop production will increase (potentially significantly) the GHG intensity of any bioenergy generated [65].

4. Results & discussion

4.1. Business case 1 – biogenic LNG

The simulation results show that there is a limited market for biogenic LNG produced by German biomethane plants underlying no change in the current legal framework. Small biomethane plants with gas flows < 250 $m^3\ h^{-1}$ are applicable to add the combined production of bio-LNG and dry ice from biogenic carbon to their sales portfolio. Sales of the jointly produced Bio-LNG and the dry ice from CO_2 separation are able to reduce the income gap from the loss of renewable energy act compensation after a guaranteed payment period of 20 years. Furthermore, the simulation results show that biomethane plants using organic waste are going to be able to produce biogenic LNG and dry ice to competitive prices. Biomethane plants using energy crops are not going to be able to do so. The amount of Bio-LNG demanded by the market depends on several assumptions about market uptake. In addition, a policy measure (blending of fossil LNG) was integrated with values of 2.5%, 5% and 7.5%. Figs. 3–5 show the simulation results for Bio-LNG market demand under varying assumptions. The illustrated demand is given by number of biomethane plants, each with a capacity of 100 $m^3\ h^{-1}$, displaying the number of biomethane plants that would be needed to fulfil the estimated demand.

The simulation results show that even though the combined production of Bio-LNG and dry ice is a possible option for small biomethane plants to compensate the losses from ending governmental support it will only be a solution for a certain amount of Germany's almost 200 biomethane plants. The simulated range varies between 4 and 16 plants in 2030 and 12 to 152 in 2035 for the scenario without blending policy. Implementing a blending policy for fossil LNG would even increase the demand for biogenic LNG and thus the number of plants needed to fulfil this demand. In the scenario with low market uptake (conservative) blending will lead to a demand of about 13 (2.5%) to 15 (7.5%) plants (Fig. 3).

The scenario with medium market uptake (moderate) will lead to higher biogenic LNG demands that could be fulfilled by 46 (2.5%) to 59 (7.5%) biomethane plants with 100 $m^3\ h^{-1}$ each (Fig. 4). High market uptake of biogenic LNG will lead to a demand of about 168 (2.5%) to 171 (7.5%) 100 $m^3\ h^{-1}$ biomethane plants (optimistic) (Fig. 5).

From the simulation results, it is obvious that blending policies only slightly increase the amount of biogenic LNG demand by the market. More important are measures that support the market uptake of biogenic LNG. Those measures encompass.

- the support of the product's attractiveness from price and environmental advantageousness,
- the support of marketing
- the support of societal awareness of the product

However, the results demonstrate that additional income my be generated for a certain group of biomethane plants smaller than 250 $m^3\ h^{-1}$ and using organic waste as feedstock. It has to be noted that first notable amounts are demanded not before 2029, which fits to the beginning of larger amounts of biomethane plants losing their REA enumeration [10].

The simulation results are of course dependent on the model assumptions. The most important are listed in Table 1 in Appendix A. The simulation reacts sensitive to changes in the market price of Bio-LNG, the price of biomethane from waste and assumptions of market uptake. Furthermore the simulation assumes the entire sale of the produced dry ice. This is a precondition for a successful business implementation. However, using a combination of novel research ideas and a market simulation model enables one to estimate the potential market uptake and the effects of no changes in the legal framework as well as changes in the current legal framework.

4.2. Business case 2 – biogenic methanol

The simulation results of BiMaSiMo show that there is currently no market potential for biogenic methanol as proposed by the here presented case study. Using the proposed boundary conditions of [68] and aligning it with similar literature BiMaSiMo estimates that there is no market uptake of this CCU pathway until 2035 if boundary conditions and the respective legal framework are not going to change

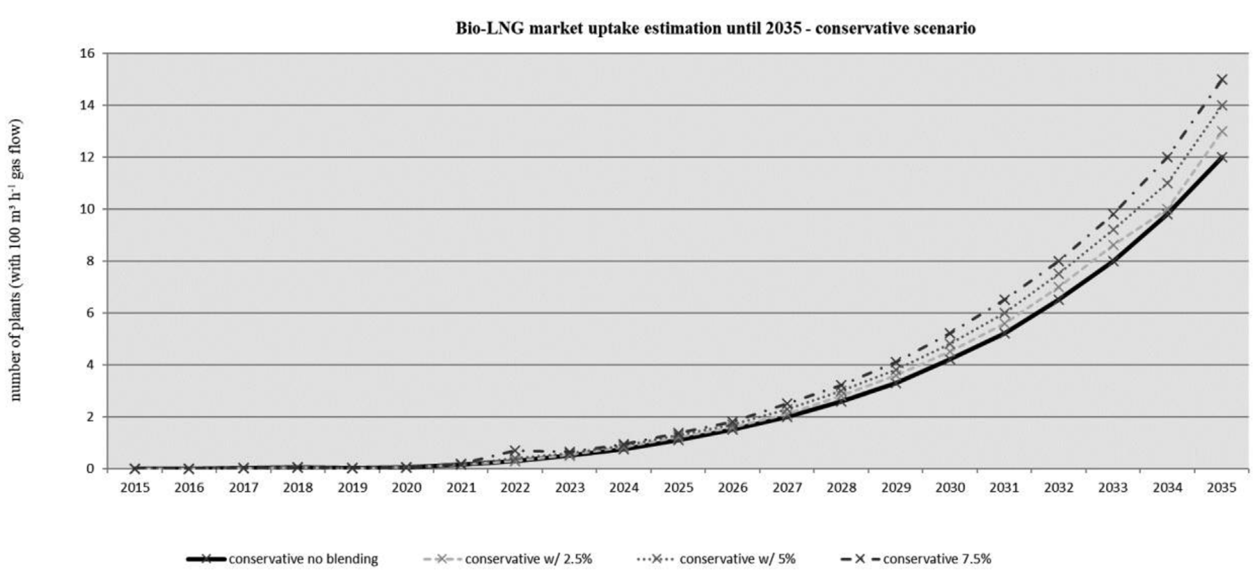

Fig. 3. Bio-LNG market uptake estimation until 2035 – conservative scenario.

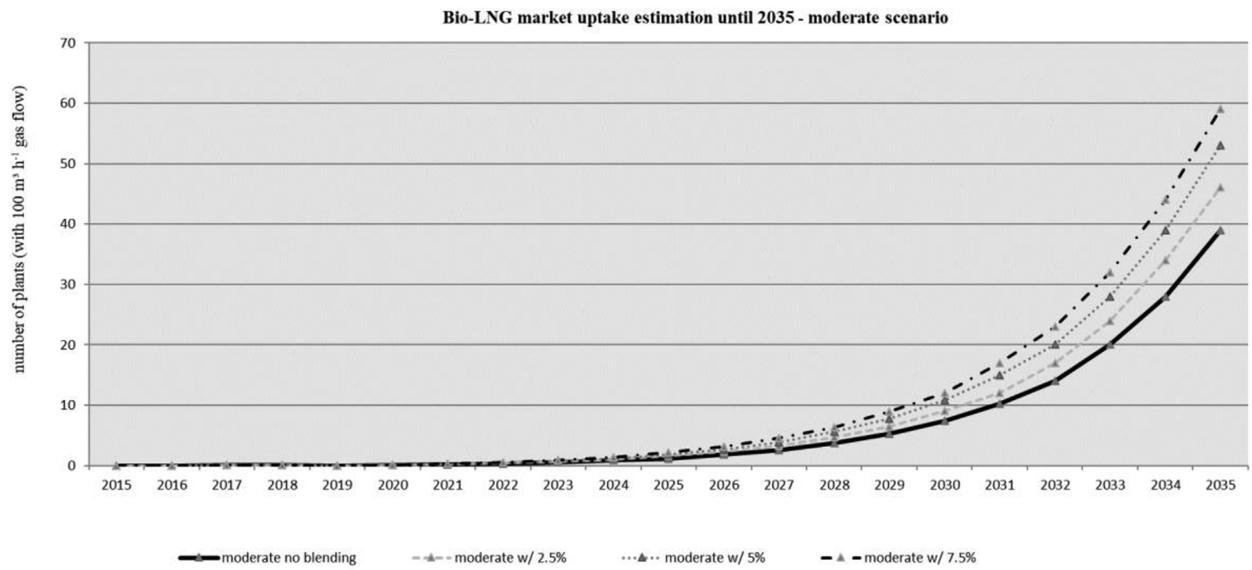

Fig. 4. Bio-LNG market uptake estimation until 2035 - moderate scenario.

dramatically. In this study we varied the price for methanol up to 500 euro Mg^{-1} which is 1.3 times the current price. However, the income gap of biogas and biomethane plants during the transition of being independent from REA compensation is not going to be closed by revenues from biogenic methanol production using H_2 and process CO_2. From the simulation results it is obvious that the methanol production at biogas and biomethane plants as a business case for the securement of a further operation seems to be unprofitable currently. However, the value of a green brand for the here proposed methanol could be a possibility to generate higher profits. As effort towards this is not seen at the moment this possibility is not part of this study.

4.3. Business case 3 – biomethane based biowax

The simulation results show that there is a limited market for the production of biowaxes by German biomethane plants underlying no change in the legal framework. Small biomethane plants with gas flows $< 120\,m^3\,h^{-1}$ are applicable to add the production of biowaxes from biogenic carbon to their sales portfolio under certain boundary conditions. In general terms it can be said that the global market for biogenic waxes is going to grow, especially for sustainable produced products [69]. The production of biowaxes by Fischer-Tropsch synthesis like it is promoted by Ref. [70] is one possibility for biomethane and biogas plants to participate in this market. However, simulation results show that with the assumed boundary conditions of Herz et al. (2017) there will be almost no market uptake of this chance. The reason for this is that the surplus income is too low to compensate the losses from expiring REA compensations for the production of renewable power. Another main reason for this is that BiMaSiMo assumes a reinvest into the biogas and biomethane producing facilities after 20 years of operation. However, using BiMaSiMo it was possible to estimate the needed requirements that would support market uptake of sustainable produced biowaxes from biogas and biomethane plants.

Fig. 6 shows the simulation results from an estimation of market uptake of biowax from biogas and biomethane plants at a biowax sales price of 4 euro kg^{-1} which is almost double the price estimated by Ref. [70]. BiMaSiMo and the aforementioned extension determines this minimum sales price to incite an investment in this technology by small

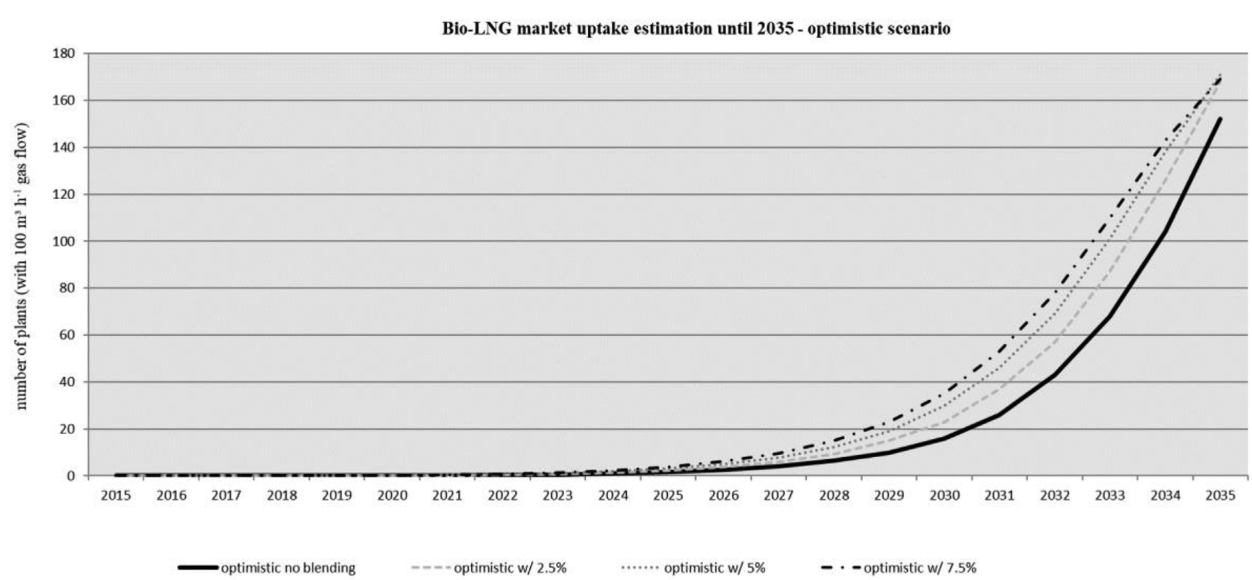

Fig. 5. Bio-LNG market uptake estimation until 2035 - optimistic scenario.

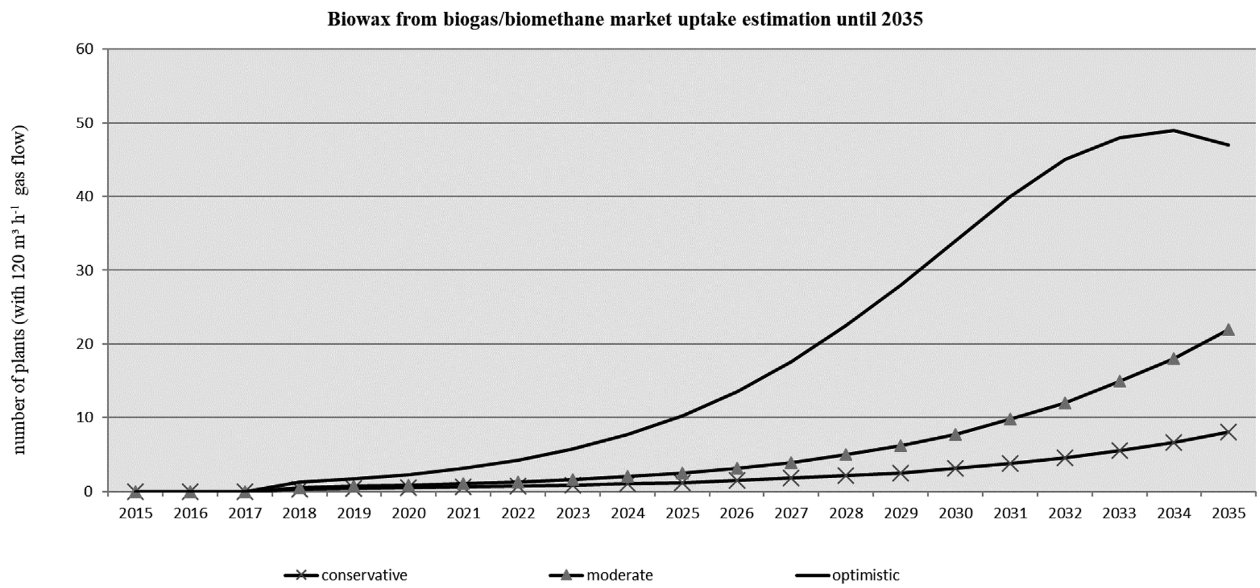

Fig. 6. Biowax from biogas/biomethane market uptake estimation until 2035.

biogas and biomethane plants. The developed extension of BiMaSiMo estimates a market for biowaxes from German biomethane and biogas plants of around 1.5 (conservative) to 13.5 (optimistic) by 2026 and 8 (conservative) to 47 (optimistic) 120 $m^3\ h^{-1}$ plants by 2034. From the simulation results it is obvious that the pathway of adoption from word-of-mouth is multiple scales higher than the adoption pathway from advertisement. The results of the optimistic market uptake scenario show that in 2034 the potential maximum is reached because the effectiveness of advertisement declines after this year. The simulation results depend on various assumptions made during the simulation set-up. The most sensitive one is the sales price for the product biowax. Further developments of the technological concept could improve the economic measures of this business case. In addition, biomethane from organic waste was used as feedstock during the simulation.

4.4. Model validation of BiMaSiMo

With a correlation close to one, the behaviour of BiMaSiMo shows high compliance with the historical data of the referral system, the German biomethane market (Fig. 7). Statistical figures in TJ a^{-1} like mean (15,871 to 16,036), minimum (0 to 283) and maximum (30,654 to 28,795) are very close. The model can therefore be characterized as a valid illustration of the real system. In addition, results of a conducted sensitivity analysis are published in Ref. [10].

5. Conclusions

In general, the field of bioenergy with carbon capture can provide a broad variety of processes and CO_2 utilizing pathways. The aim of this study was to identify economic feasible and promising business options for biomethane plants in Germany supporting the increment of independence from governmental support like compensations from REA and secure on-going biomethane production. The investigated business cases encompass the combined production of bio-LNG (biomass based liquefied natural gas) and dry ice via a cryogenic approach (business case 1), utilization of CO_2 in the chemical industry through the production of methanol (business case 2) and the production of high value chemicals like biowax (business case 3).

The combination of revenues from biomethane marketing (use for power, heat or fuel applications) and revenues from biogenic carbon dioxide marketing (business case 1 and 3) are seen as options to secure an on-going biomethane production as well as decreasing dependencies on governmental support. The combination of the potential from business case 1 and 3 results in a biomethane production capacity between 2160 $m^3\ h^{-1}$ (conservative), 6540 $m^3\ h^{-1}$ (moderate) and 20,840 $m^3\ h^{-1}$ (optimistic) (without blending policy). In comparison to the current annual production of 122,000 $m^3\ h^{-1}$ the potential can be seen as important. However, it is obvious that there are still other measures needed to secure an ongoing biomethane production in Germany. According to [10] increasing prices for emission allowances would favour biomethane production and thus the here presented business cases as well as improved communications across the diverse stakeholders in this system.

The integration of biogenic CO_2 into existing infrastructure like operating biomethane plants is a promising way to support the production of sustainable raw materials like biowax or dry ice. However, it has to be noted that a successful implementation of new technologies and thus business opportunities resulting in market uptake has to consider other aspects then economic like stakeholders and public approval and attitude, too. Specific technological concepts incorporating a combination from bioenergy and CCU can support GHG reduction in the short-term. Technologies like BECCS on the one hand seem to have higher potentials but on the other hand struggle with higher implementation barriers because they can be seen either positive or negative especially when they are used as justification to proceed with fossil fuels. Therefore, the response to BECCS technologies has to be examined besides technical and economic considerations. Otherwise, market uptake will fail.

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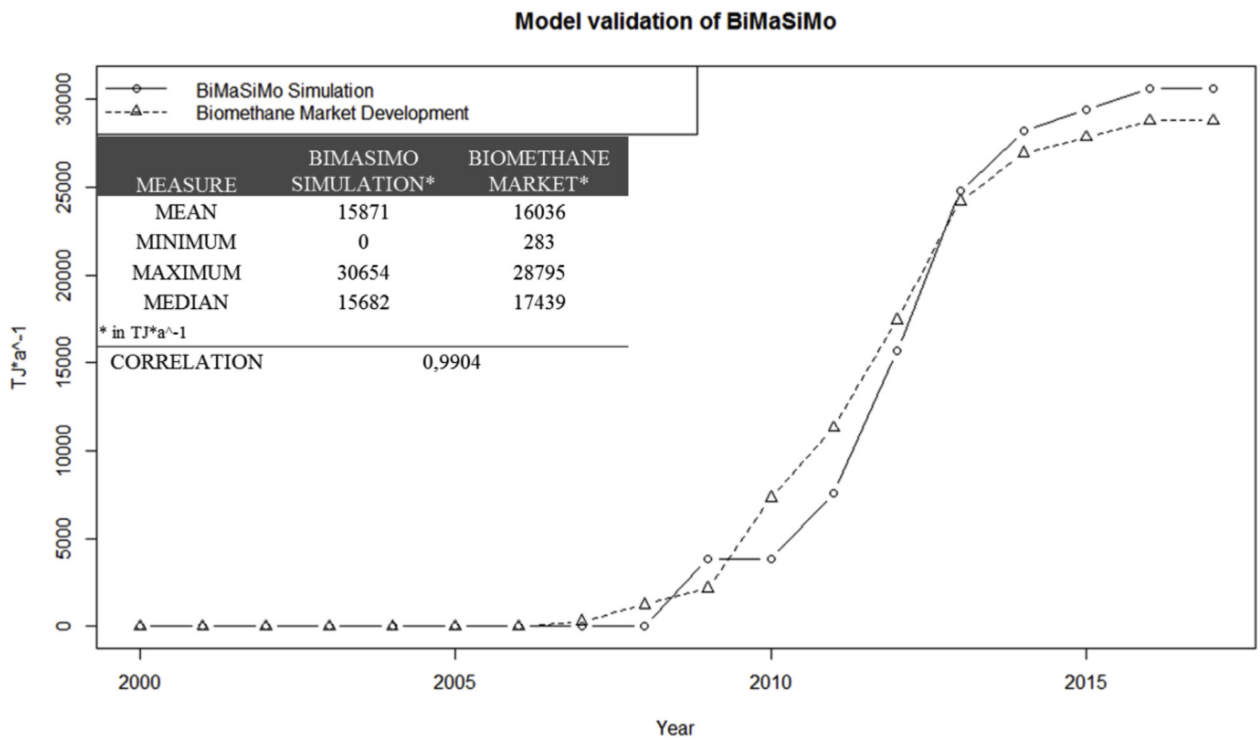

Fig. 7. Model validation of BiMaSiMo.

Appendix A

Simulation parameters business case 1

Table 1
Process assumptions for business case

parameter	assumption/numeric value	reference
dry ice and bio-LNG production	1 $m^3\ h^{-1}$ gas flow = 0.001 m^3 LNG + 1.2 kg CO_2 dry ice (including volumetric losses from transport)	[22,71,71]
system availability	85%	[22]
methane content	55%	[22]
gas flow	105 $m^3\ h^{-1}$	assumption
costs for cryogenic facility	1.5 million euro	[71]
operating costs per m^3 biogas	0.00244 euro cent	[22,71]
feedstock costs per m^3 biogas	0.004 euro cent	BiMaSiMo
transport costs m^3 bio-LNG ((100 km between production and further use))	0.001 euro cent	[22]
dry ice sales price per kg	25 euro cent	[72]
bio-LNG price at fuel stations per m^3	0,0069 euro cent	[22]
share of LNG in transport sector until 2035	10 TW h^{-1}	[73]
calorific value	0.001 m^3 LNG equals 7.6 kW h^{-1}	[74]

Simulation parameters business case 2

Table 2
Process assumptions for business case 2

parameter	assumption/numeric value	reference
catalyst type	copper and zinc based (≈523.15 K and 5–10,10^6 N · m^2-1)	[68]
catalyst amount	≈700 kg a-1	[68,75]
heat recovery	heat from synthesis (CO_2 + H_2) can cover distillation to separate methanol and water	[68]
specific investment cost for CH3OH per MW	1 million euro	[68]
CO_2 demand for 5 MW CH3OH plant	≈670 $m^3\ h^{-1}$	[68]
O&M costs	2.5% of investment	[68]
installation and demo cost	15% of investment	[68]
cost for waste biogas and upgrading per kW h^{-1}	0.06 euro	own calculations based on DBFZ data
H_2	is being bought, no detail analyse and implementation of electrolyser	
cost for H_2	0 to 5.22 euro kg^{-1}	[28]
price for methanol per MW h^{-1}	100 (optimistic) to 70 euro	[68,76]

Simulation parameters business case 3

Table 3
Process parameters for business case 3

parameter	assumption/numeric value	reference
biogas plant size	450 kW	[70]
feed stream	200 kg h^{-1}	[70]
biogas composition	60% methane, 35% carbon dioxide, 1% nitrogen, 0.3% oxygen and 3.1% water	[70]
CAPEX	digester and CHP system were depreciated	
CAPEX	2.78 million euro	[70]
OPEX per m^3	12 euro	[70]
price for synthetic crude per liter	0.45 euro	[70]
annual operating time	8000 h a^{-1}	[70]
price for sustainable wax per kg	4 euro	[70]

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